DOCUMENT RESUME

ED 477 070 IR 021 798

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TITLE	Who Learns Best with Multiple Representations? Cognitive Theory Implications for Individual Differences in Multimedia Learning.
PUB DATE	2002-06-00
NOTE	7p.; In: ED-MEDIA 2002 World Conference on Educational Multimedia, Hypermedia & Telecommunications. Proceedings (14th, Denver, Colorado, June 24-29, 2002); see IR 021 687.
AVAILABLE FROM	Association for the Advancement of Computing in Education (AACE), P.O. Box 3728, Norfolk, VA 23514. Tel: 757-623-7588; e-mail: info@aace.org; Web site: http://www.aace.org/DL/.
PUB TYPE	Reports - Research (143) -- Speeches/Meeting Papers (150)
EDRS PRICE	EDRS Price MF01/PC01 Plus Postage.
DESCRIPTORS	Cognitive Ability; *Cognitive Development; *Cognitive Measurement; Cognitive Processes; *Cognitive Style; *Computer Assisted Instruction; Computer Games; Elementary Education; Elementary School Mathematics; Elementary School Students; *Individual Differences; *Multimedia Materials

ABSTRACT

This paper presents a cognitive theory of multimedia learning from which predictions on individual differences in learning are derived and tested. Elementary students learned how to add and subtract integers with an interactive multimedia game that included visual and symbolic representations of the arithmetic procedure. They learned either with or without verbal guidance in their first language. Verbal guidance was expected to help minimize cognitive load, especially for students with low prior knowledge, low computer experience, and a less reflective cognitive style. The theoretical and practical implications of the results are discussed. (Contains 24 references.) (Author)

Who Learns Best with Multiple Representations?

Cognitive Theory Implications for Individual Differences in Multimedia Learning

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Abstract: Who learns best with multiple representations? In this paper, I present a cognitive theory of multimedia learning from which predictions on individual differences in learning are derived and tested. Elementary students learned how to add and subtract integers with an interactive multimedia game that included visual and symbolic representations of the arithmetic procedure. They learned either with or without verbal guidance in their first language. Verbal guidance was expected to help minimize cognitive load, especially for students with low prior knowledge, low computer experience, and a less reflective cognitive style. The theoretical and practical implications of the results are discussed.

Multiple Representations for Meaning Making in Math

Multimedia environments allow learners to integrate information from different representation formats and sensory modalities into one meaningful experience (Moreno & Mayer, 2000). Therefore, when an arithmetic procedure is to be taught with a multimedia program or game, the instructional designer is faced with the need to choose between several combinations of modes and modalities to promote meaningful learning. In the present review of studies, students learned to add and subtract integers by interacting with a multimedia game consisting of symbolic representations in the traditional number sentence format. In addition, based on recent advances in multimedia learning, the computer game depicts the execution of the computational procedures as visual representations of movements along a number line (Moreno & Mayer, 1999). According to the arithmetic-is-motion metaphor, "numbers are locations on a path", "the mathematical agent is a traveler along that path", "arithmetic operations are acts of moving along the path", and "the result of an arithmetic operation is a location on the path" (Lakoff & Nunez, 1997, p. 37).

For example, students select one of eight problems to solve from the problem menu. Then, students see the problem presented in symbolic form (as 4 - -5 =__) and a number line showing integers from -9 to 9 with a bunny standing at the 0 point. A simulated joystick consisting of the following four alternative moves for the bunny appears in the lower right corner: face to the left, face to the right, jump forward one step, or jump backwards one step. Students may click on any combination of the four joystick options and instantly see the resulting change in the bunny on the number line. The program instructs learners to try to figure out the problem by moving the bunny along the number line using the joystick. When students are ready to answer, they type in a numeral (and negative sign, if needed).

If the student's answer is not correct, the student may try again or see the solution to the problem. If students type in the correct answer, they hear the word "Yes" followed by an animated sequence which consists of four major steps in solving the problem. First, the symbol "4" is highlighted and the bunny moves to position 4 on the number line. Second, the minus sign is highlighted and the bunny turns to the face the left side of the screen. Third, the symbol "-5" is highlighted and the bunny makes five jumps to the right. Finally, the number "9" is highlighted and the bunny faces forward on the 9th position of the number line. Thus, the learner sees how each step in the procedure can be represented in symbols and movements. At this point, students may click on the "Back to Menu" button which takes them back to the main menu.

Would the addition of a verbal representation in the form of spoken words explaining the relationship between the visual metaphor and the symbolic sentence help students' learning? Moreover, do all students benefit from learning with more rather than fewer representations? To help answer these questions, I conducted two studies where the learning outcomes of students who learned to add and subtract integers with symbolic and visual representations (Group SV) was compared to those of students who learned the same lesson with symbolic, visual, and verbal representations (Group SVV). In particular, I concentrated on three learning measures: learning rate, pretest-to-posttest gain, and using what they have learned to solve word problems. The overarching goal of the reported studies was to explore the cognitive implications of training students with multiple representations in a high cognitive load situation and infer some preliminary principles of instructional design for individual differences in multimedia learning. In the next sections, I provide a cognitive theory of how people learn with multiple representations, introduce three possible sources of individual differences in learning from multimedia environments, and derive predictions based on the theory.

A Cognitive Theory of Multimedia Learning

The cognitive theory of multimedia learning used in the present studies draws on two main assumptions: multiple representations help learning and cognitive load hurts learning. One one hand, according to a multiple representation hypothesis, teaching with more representations facilitates and strengthens the learning process by providing several mutually referring sources of information (Kozma, Russell, Jones & Marx, 1996; Grouws, 1992; National Council of Teachers of Mathematics, 1989). For example, past studies in multimedia learning have shown that students learn math better when information is presented in verbal, visual, and symbolic formats rather than in symbolic formats alone (Moreno & Mayer, 1999), and that students learn science better from animations that include words rather than from animations or words alone (Mayer, 2001).

On the other hand, according to the thesis that cognitive load hurts learning, students' working memories are limited in capacity (Baddeley, 1986; Chandler & Sweller, 1992; Sweller, 1994). Therefore, presenting multiple representations of the same arithmetic procedure may overload the learner by creating the need to integrate the multiple sources of mutually referring information. Students with larger capacity are better able to maintain and coordinate multiple representations in working memory than are students with lower capacities (Just & Carpenter, 1992). Thus, although cognitive theory of multimedia learning supports learning with multiple representations in general, individual differences cannot be discarded (Moreno & Mayer, 1999). What are some possible sources of cognitive load differences between students?

Cognitive Tempo

Cognitive tempo (or Impulsivity/Reflectivity) refers to a person's tendency to reflect or not reflect, before responding on a problem-solving task with response uncertainty (Kagan, 1966). According to this individual difference, reflective students make fewer errors and have a longer response time than impulsive students on inductive reasoning, recognition memory, visual discrimination tasks, and serial recall (Borkowski, Peck, Reid, & Kurtz, 1983). From a theoretical perspective, it can be hypothesized that a persistent impulsive style limits students' time to reflect on the accuracy of an answer. Reflective students take more time to develop a solution hypothesis before making a choice (clicking on the computer mouse). A consequence is that deep learning becomes less likely for impulsive than for reflective students, especially where tasks carry high uncertainty and little guidance (Jonassen & Grabowski, 1993).

Prior Knowledge

Based on a cognitive theory of multimedia learning, students with high prior knowledge in arithmetic have already built their own mental model for the presented material (at least partially, for the addition and subtraction of natural numbers). Therefore, multiple representations are easier to integrate with prior knowledge and less likely to overload their working memory (Mayer, 2001; Moreno & Mayer, 1999). In addition, computer knowledge or experience (mastery of the task-specific skills that derive from interacting with a multimedia program such as clicking on buttons, typing in numbers, etc.) may affect multimedia learning. Low computer experience may impose an extra cognitive load if students are not very familiar with computers and the tasks involved in the interaction have not become automatic yet (Chandler & Sweller, 1991). This is particularly relevant for the present study because many participants are children who come from low-income, immigrant, non-English backgrounds with very few having access to computers at home.

Language Background

What are the cognitive consequences of learning verbal materials in a more versus less familiar language? An additional goal of the present study was to examine if students would choose to learn the arithmetic procedure in their first or second language given the option to do so. Knowledge of a less familiar language constrains problem solving in that language (Duran, 1985). As the computer game used for the present studies presented verbal explanations in English with the option to listen to Spanish translations, it was expected that limited English proficient students (LEP) would make significant use of the translations during training sessions. The rationale is based on the assumptions that attentional resources are limited and that in learning situations of high cognitive load such as the present one, students will be likely to lower the attentional demands by choosing to use a more familiar language.

Predictions

Based on a cognitive theory of multimedia learning, students trained with example problems presented in three different forms encode the material more deeply than those trained with problems presented in two forms (Clark & Paivio, 1991; Paivio, 1986). Moreover, cognitive load for the SVV group is minimized respect to the SV group because the extra verbal representation guides students' discovery of the relationship between the visual metaphor and the number sentence (Chandler & Sweller, 1991; Solter & Mayer, 1978; Tarmizi & Sweller, 1988). Consequently, it was predicted that compared to the SV group, the SVV group would show a larger pretest-to-posttest gain, faster rate of learning, and better transfer to solve word problems.

However, individual differences in cognitive load based on students' cognitive tempo, prior knowledge, and language background were expected. Therefore, the positive effects of multiple-representation learning should be stronger for high prior knowledge or high computer experience rather than for low prior knowledge or low computer experience students. Second, the positive effects of multiple-representation learning should be stronger for reflective rather than impulsive students. Finally, as students in Group SVV were given the option to look up the explanations in Spanish, it was predicted that limited English proficient (LEP) learners would show a greater use of Spanish explanations over sessions compared to first English proficient (FEP) learners. The rationale is based on the idea that students who are still in the transition to becoming proficient English speakers will be likely to choose their first language to lower the cognitive load required to understand the explanation of the arithmetic procedures in English.

Experiment 1: A Low Computer Experience Scenario

The first study was conducted at the beginning of the school year in a southern California elementary school where many children come from emigrant, low-income, Spanish-speaking homes. A significant proportion of students is limited English proficient and has almost no computer experience. Training with multimedia games in this scenario is very interesting as it can be argued that the visual presentation of a mathematical procedure such as the one used in the present studies can minimize the importance of language and therefore has great potential for enhancing the learning of non-native speakers of English. Second, visual instruction can build on the existing intuitive knowledge of the learner and can be particularly appropriate for less skilled students who lack formal academic training in the subject domain (Mayer, 1997). Third, visual forms of presentation can help learners build mental models of complex systems that enable problem solving rather than being subjected to rote methods of instruction that emphasize solely the acquisition of isolated facts and procedures (Grouws, 1992).

Method and Results

The participants were 61 students from three fifth and sixth-grade classrooms of an elementary school in southern California who lacked substantial prior knowledge about addition and subtraction of signed numbers. Thirty students participated in the SV group and 31 students participated in the SVV condition. Based on the school records for their English language proficiency level, students were classified as FEP or LEP. Fourteen FEP and 16 LEP students served in Group SV and 15 FEP and 16 LEP students served in Group SVV. First, each student was given the computer experience questionnaire, the paper-and-pencil pretest, and the Matching Familiar Figures test (MFFT) to determine children's cognitive tempo (Kagan, Rosman, Day, Albert, & Phillips, 1964). Second, they were randomly assigned to learn with either a SV or SVV version of the computer game and participated in each of four training sessions held on different days over a two-week period during regular class time. Finally, they were given the paper-and-pencil posttest and computerized word problem test.

For each student, the number of correct answers on the pretest was subtracted from the number of correct answers on the posttest to yield a pretest-to-posttest gain score and the number of correct answers on the word problem test, the number of correct answers on each of the training sessions, and the number of times students asked for a Spanish translation was recorded from a computer-generated log during training sessions.

Do students who learn interactively with symbolic, visual, and verbal representations show deeper understanding from a multimedia math lesson than students who learn with symbolic and visual representations alone?

Students in Group SVV had a larger mean pretest-to-posttest gain score than students in Group SV (p = .02), a marginally larger transfer to word-problem score (p = .075), and no significant difference in the learning rate. These findings suggest that instructional programs that use multiple representations (such as symbolic representations and visual interactive metaphors) are more effective when verbal explanations are explicit. However, the benefit of the verbal representation only affects students' pretest-to-posttest gain of the arithmetic procedure itself. Providing verbal representations does not affect students' learning rate and only marginally helps students transfer the procedure to solve word problems.

On the other hand, the results on individual differences showed that although prior knowledge did not affect the pretest-to posttest gain, computer experience showed a significant interaction with the type of treatment: Students who had low computer experience did not benefit from the verbal representations but students with high computer experience benefited considerably (p = .05). In addition, reflective students scored marginally higher on pretest-to-posttest gain (p = .06). Moreover, high prior knowledge students, high computer experience students, and reflective students learned faster and scored significantly higher than their counterparts in transferring the arithmetic procedure to solve word problems (p = .0001, p = .003, and p = .01 respectively for learning rates and p = .0001, p = .05, and p = .01 respectively for transfer scores). These results show that prior knowledge (both in content and computer skills) and a reflective cognitive style help students' learning by minimizing cognitive load in complex learning environments.

Do students who are in the transition to becoming English proficient use verbal explanations in their first language?

An additional issue was if LEP students in Group SVV would make significantly more use of the Spanish translations than FEP students in Group SVV. To answer this question, for each session and student, the number of times students listened to Spanish translations was recorded. Consistent with the prediction, an ANOVA with language background as a between-subjects factor and number of translations as a within-subject factor revealed a significant effect for language background, number of translations, and a significant interaction (p = 0.02, p = 0.0001, and p = 0.001, respectively). LEP students used significantly more the Spanish translations than FEP students and the number of translations decreased significantly over time for LEP students. This result is consistent with the idea that students prefer to use a more familiar to reduce the high cognitive load that results from learning with multiple representation interactive environments.

Experiment 2: A High Computer Experience Scenario

Experiment 2 was conducted at the end of the school year in a fifth and sixth grade classroom of the same elementary school that participated in Experiment 1. Contrary to the case of the first experiment, all participating students had been intensively trained in computer use for almost an entire school year. Therefore, the first goal of the second study was to test the prediction that due to students' training with computers, computer experience would lose its impact as a determinant factor in learning from the interactive program.

An additional goal of Experiment 2 was to investigate if transfer to word problems could be improved by providing explicit word problem training. The results of Experiment 1 showed an advantage of SVV instruction over SV instruction for only one of three dependent measures: pretest-to-posttest gain. Providing verbal explanations did not help students' learning rate or transfer to solve word problems. In Experiment 2, the learning of a group of students trained with symbolic, verbal, and visual representations (Group SVV) was compared to that of an identical group presented with an additional word problem for each problem type (Group SVVW). Based on past research on problem-solving transfer (Cox, 1997; Mayer & Wittrock, 1996), it was predicted that explicit training in solving word problems would result in better performance on this measure. However, as the treatments did not differ in any other aspect, differences in pretest-to-posttest gain or learning rate were not expected.

Method and Results

The participants were twenty-four students from a fifth and sixth-grade classroom of an elementary school in southern California who lacked substantial prior knowledge about addition and subtraction of signed numbers. Twelve students participated in the SVV group and 12 students participated in the SVVW condition. The procedure was identical to that used in Experiment 1 except that after students were given the computer experience questionnaire and the paper-and-pencil pretest, they were not given the MFFT because individual differences on cognitive tempo were not the focus of the study.

Do students who learn how to add and subtract integers with word problem examples show better transfer to solve word problems than students who are not presented with word problems?

Consistent with the predictions, students in Group SVVW and SVV did not differ in their mean pretest-to-posttest gain or in their learning rate. However, the main prediction was that providing word problem examples to Group SVVW would make a significant difference in the transfer to a word problem test respect to Group SVV. Consistent with this prediction, using transfer to word problems as a dependent measure, a one-factor ANOVA revealed a treatment effect ($p = .05$). Students in Group SVVW were significantly better able to transfer the arithmetic procedure to solve word problems as compared to students in Group SVV.

What is the role of computer experience for students who learn with multiple representations in a computer-trained classroom?

Due to students' overall high experience with computers, it was expected that computer knowledge would not affect overall performance because they had automated the computer skills necessary to interact with the program. Consistent with the predictions, the statistical analyses revealed no computer experience effect on pretest-to-posttest gains, learning rate, or transfer to word problems. High experience students scored comparably to low experience students on all dependent measures. As argued in the predictions, the different pattern of results between both studies can be interpreted as due to the computer training program that the teacher had implemented in the participating class. Experiment 1 was conducted at the beginning of the school year and many students reported having very low or even no basic computer experience. On the other hand, Experiment 2 was conducted in a classroom where the teacher placed priority on students' practice of technologically based instructional materials. For example, one of the goals of the participating class consisted of having each student develop their own web page by the end of the year.

General Discussion

Multimedia programs allow students to work easily with multiple representations of complex systems. The reported studies demonstrate that presenting a symbolic and visual representation of how an arithmetic procedure works does not insure that all students will understand the explanation unless cognitive theory is applied to the design.

The reported studies have important implications. Theoretically, this research supports a cognitive theory of multimedia learning in two ways. First, by demonstrating that teaching with symbolic, visual, and verbal representations facilitates and strengthens the learning process by providing several mutually referring sources of information. Second, by suggesting that the additional cognitive load imposed on the SV group (i.e., the need for students to use their limited cognitive resources to discover the meaning of a procedure and generate their own verbal representation) is detrimental to learning by exhausting working memory capacity. Third, the results from Experiments 1 and 2 show that even when instructional methods are grounded on visual metaphors, transfer skills require explicit training. Although interactive visual metaphors may help students build connections between arbitrary sets of procedures that use symbols and their informal conceptual knowledge, this method only seems to help students understand the arithmetic procedure itself. Finally, congruent with cognitive load theory, when learners are required to mentally integrate disparate sources of mutually referring information, such split-source information may create a heavy cognitive load that disrupts learning, especially for learners who have fewer cognitive resources (Moreno & Mayer, 1999; Sweller, 1991). The present results on individual differences are consistent with the interpretation that students learn deeper in multimedia interactive environments when the advantages of multiple representations are not outweighed by individual differences in cognitive load (Chandler & Sweller, 1991; Sweller, 1994).

On the practical side, the overall results indicate that visual metaphors need verbal guidance and word problem examples if they are to be used as an instructional tool to foster mathematical understanding and transfer. Multimedia environments have the capability of creating dynamic visual representations of constructs that are frequently missing in the mental models of novices (Kozma, 1991). However, the present findings show that for multimedia learning to be effective it is important to design the materials in a manner that minimizes cognitive load. One way to reduce cognitive load is by providing guidance in the form of verbal explanations in students' first language. A contribution of the reported studies is to identify computer experience, prior knowledge, and cognitive tempo as important factors that help students learn from multimedia by minimizing cognitive load.

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